DETERMINATION OF RATIO & ANGLE ERRORS
IN A
SERIES TRANSFORMER

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DETERMINATION
OF
RATIO AND ANGLE ERRORS
IN A
SERIES TRANSFORMER

A THESIS

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PREFACE.

The object of this thesis is to find a satisfactory method of determining the Ratio and Angle Errors of a Current or Series Transformer, and of using this method to make a complete test on one type of transformer.

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INTRODUCTION.

INTRODUCTION.

A Current Transformer is used in A. C. circuits for the same purpose that a shunt is used in D. C. circuits; ie, to keep large leads and high potentials from the switchboard. With large currents the size of the conductors often makes the expense of running them to the switchboard excessive. In This case a current transformer is placed with its primary in the main circuit and its secondary connected to the instrument leads from the switchboard. The secondary is generally designed for a maximum of five amperes and a number 14 B & S wire is all that is necessary to carry this current thus saving considerable expense in copper. In high potential plants the current transformer protects the switchboard and attendants from the danger of grounds. One side of the secondry is grounded and if the other side becomes grounded on the switchboard there can never be a potential much in excess of 50 volts. A higher potential on the sec-

ondry is only possible when it becomes open circuited, when it may become several thousand volts.

The series transformer, not considering its design, differs from the shunt transformer merely in its method of use. With the shunt transformer the primary is connected directly across the mains and the load varied by varying the total impediance of the secondry circuit, its object being to step down the voltage of transmission to that of use. With the series transformer the primary is connected in series with the mains. Its total secondry impediance is constant,(consisting of ammeters, wattmeters, relays and leads) and the load is varied by varying the current in the primary. Thus it is seen that the actual ratio of,and angle between the primary and secondry currents in the shunt transformer is of little importance; while with the series, in order that the instruments give a true indication of the power they are of the greatest import-

ance.

For use with an ammeter it is desirable for the secondry current to be directly proportional to the primary, and for use with a wattmeter it is further necessary that the primary and secondry currents be as nearly as possible to 180° apart and in time phase. If the core loss current and the exciting current could be reduced to zero in a current transformer it would be perfectly accurate as far as angle error is concerned. A change in the resistance or impediance of the secondry circuit changes these currents, therefore the seconary circuits should have a minimum possible impediance. The exciting current and iron loss current can also be reduced by using a core with a high permeability and low iron loss.

DESCRIPTION.

of

TRANSFORMER TESTED.

DESCRIPTION OF TRANSFORMER TESTED.

NAME PLATE.

CURRENT TRANSFORMER.
No. 184238
Spec. No 2516 Type S
Form E Cycles 25/125
Watts 40
Normal load 1000 Amp.
30 min. load 1500 Amp.
Ratio 300 to 1.
For 6600 volt circuit.
GENERAL ELECTRIC CO.
Schnectady, N.Y. U.S.A.

The transformer tested is shown on Plate II. The primary consists of a round copper bar 1 1/8" in diameter. There is then a layer of 3/8" tape. The inside secondry windings then take up 3/8" and there is then a 1/16" of tape. The core is next and con-

sists of rings of iron laminations .0135" thick with an inside diameter of 2 3/4" and outside of 4 3/4". Then there is a 1/16" tape and then the secondry windings and finally 1/4" tape. The total diameter is thus 5 1/4". The length of the laminated core is 2 1/8" with 7/16" tape and paper insulation on each end, making a total of 3". The secondary windings are of #16 B & S wire and had a résistance of .078 ohms.

METHOD OF PROCEDURE

METHOD OF PROCEDURE

A scheme of the connections is shown on Plate I. A three phase, squirrel cage, induction motor with its secondary open and connected to slip rings was used as a phase shifter and the rotor was blocked so that it could be shifted at will. A high current transformer of sufficient carrying capacity was not available, so two series transformers of the same capacity as the one tested were connected in series to supply the large primary current. The load was varied by means of the lamp rack shown in the secondary circuit; and the current in the secondary of the dynamometer was kept at about three amperes by means of the lamp rack in its circuit. A mercury ammeter was placed in the primary circuit to obtain the primary current.

The secondary circuits used were as near as possible those that would be used in practice, with the exception of Circuit #5

which consists of a high inductance.

Before connecting up, the instruments were all calibrated and calibration curves plotted, from which the true values were obtained. To do this the dynamometer was calibrated as an ammeter, on direct current, and as the two coils were connected in series the value of the cosine was one and I_1 equals I_2; therefore $D = KI^2$. The values of K for different deflections were plotted so that these values could be taken off. The ammeters were then connected in series with the dynamometer and calibrated on alternating current.

The resistances of the secondary circuits tested were obtained by means of a Wheatstone Bridge. The impediances of the secondary circuits were obtained by passing a sine wave of current through them and measuring the current and drop across them. The sine wave was obtained by balancing

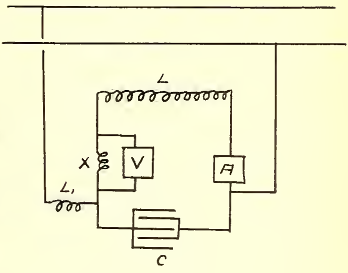

Figure I

inductances and condensers against one another as shown in Fig. 1. The oscillograph was used to tell when a sine wave was obtained. The drop across the circuit was measured by a hot wire ammeter calibrated as a voltmeter.

On Page 20. is given in tabulated form a description of the secondary circuits used and also a list of the instruments used.

A load was first placed upon the transformer to be tested by varying the current in the secondary of the other transformers. The switch was then thrown so as to place the moving coil of the dynamometer across the shunt and the phase shifter was balanced till there was no deflection of the dynamometer or the two currents were 90° apart. A switch was connected across the secondary of the transformer to be tested so that while this was being done the terminals could be short circuited and thus prevent an excessive potential being induced in the

secondary, due to the current in the primary, and puncturing the insulation. The switch was then thrown, placing the secondary of the current transformer across the dynamometer, and the deflection angle read off. Knowing the currznt in the two coils of the dynanometer, the constant was obtained from the curve and the angle calculated.

CALCULATIONS

CALCULATIONS

The following is the method used for calculating, from the experimental data, the data used for plotting the curves. The corrected values as obtained from the calibration curve of the instruments were used in each case.

The ratio was obtained directly from the mercuary ammeter in the primary circuit and the ammeter in the secondary circuit. The ratio error then is in per cent,- The apparent ratio minus the true ratio divided by the true ratio, the whole multiplied by 100 or,-

$$\text{Error} = \frac{\text{App. R} - 300}{300} \text{ X } 100$$

In obtaining the angle error let E_1 = primary E.M.F. (Fig. 2) Cos θ = power factor, I_1 = prim. current, E_2 = secondary current. Then if there was no impediance in the secondary circuit or no iron or magnetizing current in the transformer I_2^1 would be the secondary current and

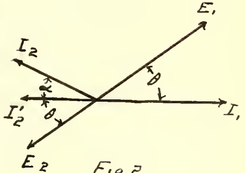

Fig 2.

there would be no angle error; but, owing to the above the secondary lags behind I_2^1 by the angle a and is represented by I_2.

In the primary the power is $E_1I_1\cos\theta$. Assuming a one to one ratio the recorded power on the secondary side is $E_2I_2\cos(\theta + a)$ but the true power is $E_2I_2\cos\theta$ as it is proportional to the power on the primary side. The per cent error is therefore:-

$$\text{Error} = \frac{E_2I_2\cos\theta - E_2I_2\cos(\theta + a)}{E_2I_2\cos\theta} \times 100$$

$$= \left(1 - \frac{\cos(\theta + a)}{\cos\theta}\right) \times 100$$

To get the total error we add the angle and ratio error together. Now we will call the error in favor of the consumer a positive error. Then as a is a lagging angle its error is always in favor of the consumer. Also when the ratio error is positive it is in favor of the consumer, so that the algebraic sum of the errors gives the total error.

SAMPLE CALCULATIONS

Example Circuit#4.

$I_b = 3.67$ $I_p = 500$ amp.

$I_s = 1.664$ Def. 3.02

RATIO ERROR.

Ratio = 500/1.664 = 30.77

Error = (3o7.7 - 300/300) X 100 = 2.56 %

ANGLE a

$D = KI_1I_2 \sin a$

K is obtained from Curve on Plate XXII.

$\sin.a = D/KI_1I_2 = 3.02/3.67 \times 1.664 \times 25.84$

$= .01952$

$a = 1^\circ\ 7'$

ANGLE ERROR.

$P\text{-}F = .75$ $\theta = 41^\circ\ 25'$

$$\text{Error} = \left(1 - \frac{\cos(\theta + a)}{\cos\theta}\right) \times 100$$

$$\left(1 - \frac{\text{cas}(41^\circ 25' + 1^\circ\ 7')}{\cos 41^\circ\ 25'}\right) \times 100$$

$$= \left(1 - \frac{.73688}{.75000}\right) \times 100 = 1.75\ \%$$

TOTAL ERROR = 2.56 + 1.75 = 4.31 %

LIST OF CIRCUITS

	#1	#3	#2	#4	#5
Ammeter	1	1	2	2	1
Integrating Wattmeter.			2	2	
Res.-200ft #14 B & S			1	1	
Relay.		1		1	
Resistance	.01275	.0665	2.2045	2.7272	.134
Z	.165	1.83	2.59	5.96	18.92
X	.164	1.825	1.902	5.263	18.92
L	.00104	.01175	.01285	.03349	.1144

LIST OF INSTRUMENTS.

Thompson Houston Ammeter (0-5) #111,755

Thompson Houston Ammeter (0-5) #144,085

Thompson Houston Ammeter (0-2) #142,640

Thompson Houston Ammeter (0)10) #140,936

Mercuary Ammeter (0-1000)

Sangamo ElectricIns. Wattmeter. Type F.

Ferranti Inst. Wattmeter # 224,320

General Electric Relay.

DATA

CIRCUIT #I.

I_B	Def.	K	I_p	I_s	Ratio	Sin. a	a
3.64	.95	25.48	100	.335	29.78	.03050	1° 45'
3.67	1.47	25.49	200	.689	29.63	.02181	1° 15'
3.64	1.71	25.48	300	1.031	29.52	.01745	1° 0'
3.64	2.59	25.48	400	1.359	29.44	.01658	57'
3.63	2.72	25.48	500	1.682	29.45	.01600	55'
3.66	3.00	25.49	600	2.031	29.26	.01571	54'
3.65	4.02	25.48	708	2.380	29.17	.01542	53'
3.61	7.59	25.47	1265	4.221	28.73	.01425	49'
3.61	7.32	25.47	1440	4.840	28.56	.01367	47'

CIRCUIT #II

I_b	Def.	K	I_p	I_s	Ratio	Sin. a	a
3.16	.81	25.40	100	.325	30.76	.02690	1° 33'
3.66	1.42	25.48	200	.670	30.57	.02260	1° 18'
3.62	2.01	25.49	300	1.075	30.44	.02022	1° 10'
3.59	2.31	25.49	400	1.328	30.34	.01902	1° 5'
3.58	2.65	25.48	500	1.682	30.31	.01902	1° 5'
3.55	3.89	25.48	600	1.990	30.30	.01902	1° 5'
3.51	4.30	25.47	708	2.315	30.30	.01875	1° 4'
3.46	7.31	25.47	1330	4.390	30.27	.01832	1° 3'

CIRCUIT #III.

I_b	Defl.	K	I_p	I_s	Ratio	Sin. a	a
3.73	.45	25.49	100	.315	30.71	.03257	1° 52'
3.76	.80	25.49	200	.674	30.35	.02036	1° 10'
3.80	1.50	25.49	300	1.000	30	.01658	57'
3.73	1.95	25.49	400	1.335	29.91	.01571	54'
3.73	2.51	25.49	500	1.705	29.89	.01571	54'
3.73	2.88	25.49	600	2.015	29.83	.01571	54'
3.69	3.6	25.48	700	2.351	29.80	.01542	53'
3.66	4.34	25.48	828	2.825	29.87	.01513	52'
3.71	5.8	25.49	1256	4.230	29.65	.01483	51'
3.70	7.8	25.49	1466	4.950	29.58	.01540	50'

CIRCUIT #IV.

I_b	Defl.	K	I_p	I_s	Ratio	Sin. a	a
3.77	.61	25.49	100	.310	32.20	.02908	1° 40'
3.73	1.40	25.49	200	.664	31.55	.02320	1° 21'
3.67	1.92	25.48	300	.991	31.13	.02041	1° 10'
3.67	2.40	25.48	400	1.32	30.92	.01950	1° 7'
3.67	3.02	25.48	500	1.664	30.77	.01952	1° 7'
3.66	3.81	25.48	600	1.970	30.66	.01942	1° 7'
3.65	4.20	25.48	708	2.321	30.57	.01934	1° 6'
3.63	5.00	25.47	765	2.470	30.52	.01891	1° 5'
3.62	7.21	25.47	1208	3.980	30.36	.01891	1° 5'
3.66	9.2	25.48	1361	4.43	30.33	.01803	1° 2'

CIRCUIT #V.

I_b	Defl.	K	I_p	I_s	Ratio	Sin. a	a
2.54	1.05	25.42	100	.321	32.20	.06461	3° 42'
3.37	1.61	25.47	200	.642	31.95	.04217	2° 25'
3.55	3.54	25.47	300	.96	31.77	.03723	2° 8'
3.53	3.81	25.47	400	1.263	31.61	.03577	2° 3'
3.51	5.87	25.07	500	1.611	31.49	.03519	2° 1'
3.53	6.22	25.47	600	1.920	31.40	.03490	2° 0'
3.97	7.71	25.48	708	2.260	31.33	.03490	2° 0'
3.31	9.9	25.46	752	2.410	31.30	.03461	1° 59'

Circuit #I.

ANGLES ERRORS.

I_P	a	P. F. -.9	P.F. 1	P.F. .9	P.F. .75
100	1° 45'	-1.44	.047	1.63	2.75
200	1° 15'	-1.04	.024	1.07	2.06
300	1° 0'	- .84	.015	.85	1.57
400	57'	- .80	.014	.81	1.49
500	55'	- .77	.013	.78	1.44
600	54'	- .76	.012	.77	1.41
708	53'	- .74	.012	.75	1.38
1265	49'	- .69	.010	.69	1.27
1440	47'	- .66	.009	.66	1.23

Circuit #II

ANGLE ERRORS.

I_p	a	P. F. -.9	P.F. 1	P.F. .9	P.F. .75
100	1° 33'	-1.28	.027	1.34	2.43
200	1° 18'	-1.08	.026	1.12	2.04
300	1° 10'	- .97	.021	1.00	1.83
400	1° 5'	- .90	.018	.93	1.69
500	1° 5'	- .90	.018	.93	1.69
600	1° 5'	- .90	.018	.93	1.69
708	1° 4'	- .90	.017	.92	1.67
1330	1° 3'	- .88	.017	.90	1.64

Circuit #III.

ANGLE ERRORS.

I_P	a	P. F. -.9	P.F. 1	P.F. .9	P.F. .75
100	1° 52'	-1.53	.06	1.63	2.94
200	1° 10'	- .97	.021	1.00	1.63
300	57'	- .80	.014	.81	1.49
400	54'	- .76	.018	.77	1.41
500	54'	- .76	.018	.77	1.41
600	54'	- .76	.018	.77	1.41
708	53'	- .74	.012	.75	1.38
828	52'	- .73	.01	.74	1.36
1256	51'	- .71	.01	.72	1.34
1466	50'	- .7	.01	.71	1.31

Circuit #IV.

ANGLE ERRORS.

I_F	a	P.F. +.9	P.F. 1	P.F. .9	P.F. .75
100	1° 40'	-1.73	.042	1.45	2.62
200	1° 20'	-1.11	.027	1.14	2.17
300	1° 10'	- .97	.021	1.00	1.83
400	1° 7'	- .93	.029	.96	1.75
500	1° 7'	- .93	.029	.96	1.75
600	1° 7'	- .93	.029	.96	1.75
708	1° 6'	- .92	.018	.94	1.73
765	1° 5'	- .90	.018	.93	1.19
1208	1° 3'	- .83	.017	.90	1.64
1361	1° 2'	- .86	.016	.87	1.61

Circuit #V.

ANGLE ERRORS.

I_p	a	P. F. -.9	P.F. 1	P.F. .9	P.F. .75
100	3° 42'	-2.80	1.08	3.31	5.91
200	2° 25'	-1.96	.89	2.12	3.84
300	2° 8'	-1.74	.69	1.86	3.36
400	2° 3'	-1.68	.64	1.79	3.23
500	2° 1'	-1.65	.62	1.76	3.18
600	2° 0'	-1.64	.61	1.74	3.15
708	2° 0'	-1.64	.61	1.74	3.15
752	1° 59'	-1.62	.60	1.73	3.12

Circuit #I.

RATIO & TOTAL ERRORS.

I_p	Ratio	P. F.	P. F.	P. F.	P. F.
100	- .73	-2.17	- .68	.89	2.02
200	-1.33	-2.37	-1.30	- .26	- .17
300	-1.60	-2.44	-1.74	- .75	- .03
400	-1.83	-2.66	-1.75	-1.05	- .37
500	-1.66	-2.63	-1.45	-1.08	- .42
600	-2.46	-3.22	-2.35	-1.69	- 1.05
708	-2.76	-3.50	-2.75	-2.01	-1.38
1265	-4.22	-4.99	-4.22	-3.53	-2.94
1440	-4.81	-5.47	-4.80	-4.15	-3.58

Circuit #11

RATIO & TOTAL ERRORS.

I_p	Ratio Error	P. F. -.9	P. F. 1	P. F. .9	P. F. .75
100	2.52	2.34	2.53	3.86	4.95
200	1.86	.95	1.89	2.98	3.90
300	1.46	.49	1.48	2.46	3.29
400	1.13	.23	1.15	2.06	2.82
500	1.03	.13	1.04	1.96	2.72
600	1.00	.10	1.02	1.93	2.69
708	1.00	.10	1.02	1.92	2.67
1330	.90	.02	.92	1.80	2.54

Circuit #III.

RATIO & TOTAL ERRORS.

I_p	Ratio Error	P. F. -.9	P. F. 1	P. F. .9	P. F. .75
100	2.36	.73	2.42	4.99	5.30
200	1.17	.20	1.19	2.17	3.00
300	0.00	- .80	.01	.81	1.49
400	- .30	-1.06	- .29	.47	1.11
500	- .36	-1.12	- .35	.41	1.05
600	- .57	-1.33	- .56	.20	.84
708	- .66	-1.40	- .65	.09	.72
828	- .43	-1.16	- .42	.31	.92
1256	-1.16	-1.87	-1.15	- .44	.18
1466	-1.40	-2.10	-1.39	- .69	- .09

Circuit #IV.

RATIO & TOTAL ERROR.

I_p	Ratio Error	P. F. -.9	P. F. 1	P. F. .9	P. F. .75
100	7.3	6.93	7.34	8.75	9.92
200	5.15	4.04	5.18	6.23	7.32
300	3.76	2.79	3.79	4.76	5.59
400	3.05	2.12	3.08	4.01	4.80
500	2.56	1.63	2.58	3.52	4.31
600	2.20	1.17	2.22	3.16	3.95
708	1.91	.98	1.92	2.84	3.63
765	1.73	.83	1.75	2.66	3.42
1208	1.20	.32	1.22	2.10	2.84
1361	1.10	.24	1.12	1.97	2.41

Circuit #V.

RATIO & TOTAL ERROR.

I_p	Ratio Error	P.F. -.9	P.F. 1	P. F. .9	P. F. .75
100	7.35	4.45	9.43	10.66	13.26
200	6.50	4.54	7.39	8.62	10.34
300	5.88	4.14	6.57	7.74	9.24
400	5.36	3.68	6.00	7.15	8.59
500	4.95	3.30	5.57	6.71	8.13
600	4.67	3.03	5.25	6.41	7.82
708	4.42	2.78	5.03	6.16	7.57
752	4.33	2.71	4.93	6.06	7.45

TOTAL ERRORS FOR DIFFERENT POWER FACTORS.

Cir.	I_p	P. F. .10	P. F. .25	P. F. .50	P. F. .75	P. F. .90
I	100	30.22	7.59	3.08	2.02	.89
I	500	22.58	4.22	.92	- .42	-1.08
I	1000	20.03	.23	- .67	-1.89	-2.51
II	100	37.99	12.70	7.26	4.98	3.86
II	500	26.92	8.23	4.33	2.72	1.96
II	1000	21.94	7.03	3.75	2.39	1.74
III	100	34.05	11.28	6.49	5.30	4.99
III	500	24.95	5.04	2.48	1.05	.41
III	1000	22.68	4.83	- .26	- .47	- .25
IV	100	44.8	28.46	12.38	9.92	8.75
IV	500	30.48	10.00	5.96	4.31	3.42
IV	1000	28.55	8.58	4.76	2.18	2.48
V	100	80.30	32.43	16.67	13.26	10.66
V	500	48.55	18.51	11.11	8.13	6.71
V	1000	46.35	17.20	10.10	7.12	5.89

TOTAL ERRORS FOR DIFFERENT POWER FACTORS.

Cir.	I_p	P. F. 1	P. F. -.9	P. F. -.75	P. F. -.50	P. F. -.25
I	100	- .68	-2.17	-2.54	-4.47	- 9.29
I	500	-1.75	-2.36	-3.34	-4.60	- 8.18
I	1000	-3.23	-3.97	-3.89	-5.79	- 9.13
II	100	2.53	2.34	.20	-2.12	- 8.04
II	500	1.04	.13	- .61	-2.71	- 6.41
II	1000	.97	.12	- .43	-2.89	-5.37
III	100	2.42	.73	.36	-1.64	-6.76
III	500	.35	-1.12	-1.80	-4.26	-7.00
III	1000	- .87	-1.62	-2.51	-2.49	- 6.89
IV	100	7.34	6.93	4.88	2.32	- 2.86
IV	500	2.58	1.63	.88	.80	- 3.12
IV	1000	1.52	.42	-.10	-1.18	- 5.82
V	100	9.43	4.45	1.87	-3.09	-17.57
V	500	5.57	3.30	1.95	-1.09	- 8.73
V	1000	4.24	5.62	1.42	-1.58	- 7.96

CONCLUSIONS

CONCLUSIONS

The secondary circuits used, were as near as possible equivalent to those used in ordinary practice. Circuit #1 consists simply of an ammeter and very short leads while Circuit #3 had a relay added. Circuit #2 consisted of two ammeters, 2 wattmeters, and a resistance equivalent to 200 ft of #14 B & S wire. Circuit #4 was the same as #2 with a relay added and could be considered as equal to the circuits generally found in practice. Circuit #5 consists of a very high inductance.

Of the curves obtained;-

Plates III to VII show the angles, ratios, and secondary currents for different loads for the different circuits.

Plates VIII shows the ratio errors.

Plates IX to XII show the angle errors with the different loads for the different circuits and for different powerfactors.

Plates XIII to XVI show the total errors with different loads for the different circuits and for different power factors.

Plate XVII to XXI show the effects of varying the power factor on the total error for the different circuits.

Plates XXV to XXXIV shows oscillograms taken in the primary and secondary circuits for different secondary circuits and different loads.

From a study of the curves it is seen that the ratio and size of the angle error depends not so much on the resistance and reactance of the secondary circuits as on the combination of them or the impedance. Thus in Circuit #5 which is composed nearly entirely of inductance (X - 18.92 and R - .134) a resistance as high as two ohms was placed in the circuit without altering the results appreciably while in circuit #2 where the inductance and the resistance are nearly equal (X - 1.902 and R - 2,2) a small change in either the inductance or the resistance was easily noticable in the results. This is seen in the difference between curves of Circuits II and IV where the resistances are nearly the same but the inductance of IV is larger (being X - 5.26 &

X - 1.9) than that of II. It is seen that the angle error of IV is, at 1000 amperes primary current, 1° 5' while that of II is 1°; While the ratio of IV is 30.5 and that of II 30.2.

The effect of a change of resistance when the inductance is constant is shown by Circuits #2 & #3, where X - 1.9 and 1.82 respectivelly and R - 2.2 and .06 ohms. The ratios are 30.2 and 29.7 and the angle errors 1° and 50' respectivelly with primary currents of 1000 amperes.

The ratio errors are shown better on Plate VIII where it is seen that Circuit #4 having greater inductance and same resistance as Circuit #2 has a greater ratio error, while Circuit #2 having equal inductance but greater resistance that Circuit #3 has a positive ratio error and #3 a negative one. This also shows that the transformer was designed for circuits similar to #2 and #3.

The same is shown by Plates IV to XII as regards to the angle error. With regards to

the total error we have the same general effect, but with different power factors, the angle errors change from positive to negative and is thus for lagging currents added to, and for leading currents subtracted from the ratio error.

From the above the conclusion is drawn that the errors, both ratio and angle, depend upon the total impedance of the secondary circuit, and not so much upon its component parts; ie, resistance and inductance. Thus a change in the largest component greatly effects the accuracy in as much as it effects the value of the impedance while a change in the smaller component does not effect the results so much as it does not alter the impediance much.

It is interesting to study Plates XVII to XXI where the total errors for different power factors are plotted for the different circuits. As the power factor of a station is generally from .75 to 1 with a lagging current the errors between these values will

be considered. With circuit #1 where Z - .165 ohms the error between these two points does not exceed 1.5%. In circuit #3 with Z- 1.83 ohms the error becomes as large as 2.2 % with 100 amperes while for 1000 amperes it is practically the same. In circuit #2, Z - 2.89 ohms, the error is increased to 3.5 for 100 amperes. It will also be noted that the curves are practically the same as those considered but the errors have all become positive. Circuit #4, Z - 5.96 ohms, the errors have become larger and positive, that for 100 amperes being as high as 10 % while those for 1000 amperes are still within 3 %. In circuit #5, Z - 18.92, we have still greater errors between these limits. This, however, is a distorted condition, as the secondary or instrument circuit would never have an impedance as high as this, but it is interesting to note that with low power factors the errors become exceedingly high running up to 80 % in favour of the consumer on the light loads.

From the curves it is seen that:-

(1) Increasing the impedance the error is increased positively.

(2) With low powerfactors and leading current the error is negative and with low power factors lagging currents the error is large in a positive direction.

(3) That the smaller the load the greater the error in a positive direction.

While running the tests we took oscillograms of the primary and secondary currents for the different circuits and different loads. The wave shape of the primary circuits does not vary much for the different circuits but on the secondary side the wave is more peaked with the lower impediances. This is probably due to the inductance.

PLATES

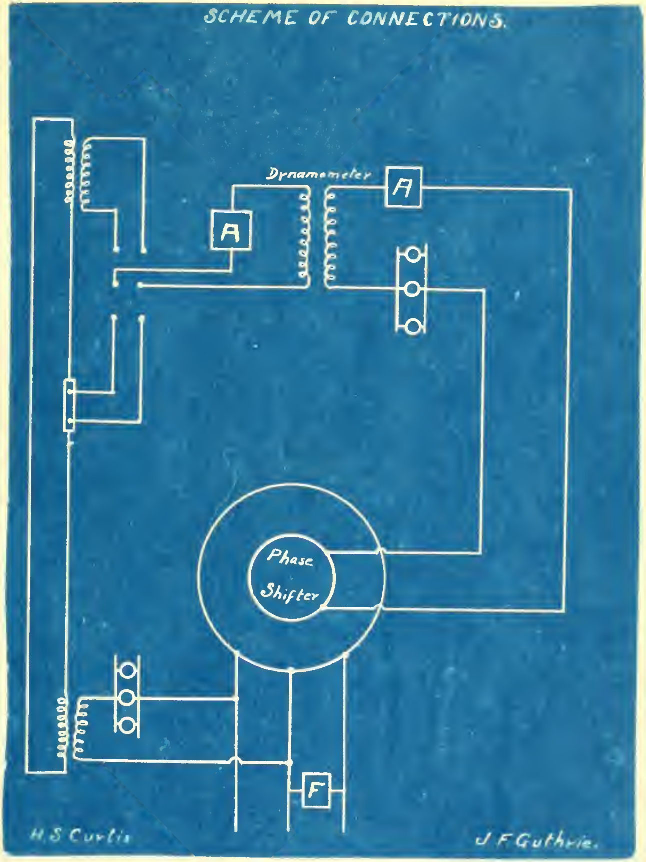
SCHEME OF CONNECTIONS.
Dynamometer
A
A
Phase Shifter
F
H.S Curtis
J F Guthrie.

PLATE. I.

ARMOUR
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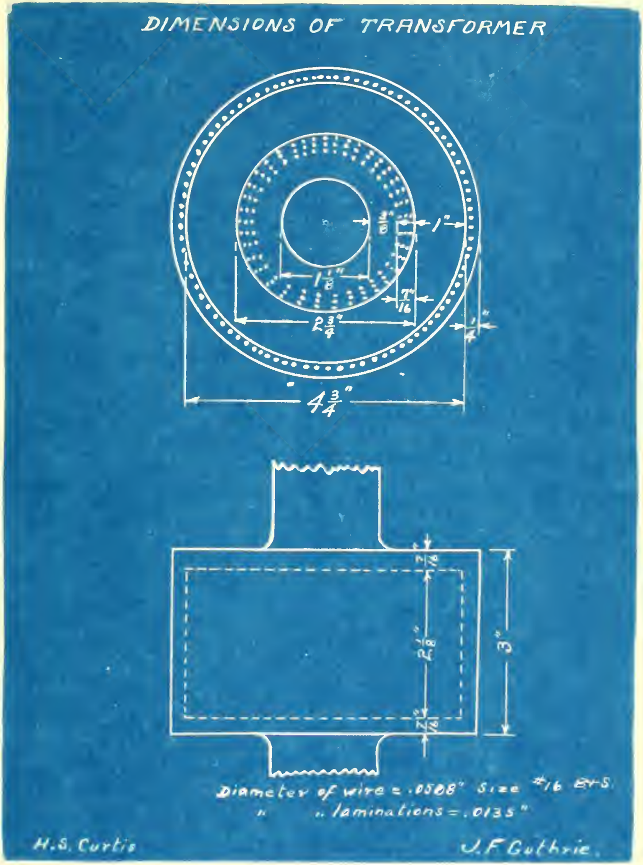
LIBRARY



DIMENSIONS OF TRANSFORMER

Diameter of wire = .0508" Size #16 B+S.
" " laminations = .0135"

H.S. Curtis

J.F Guthrie.

PLATE II.

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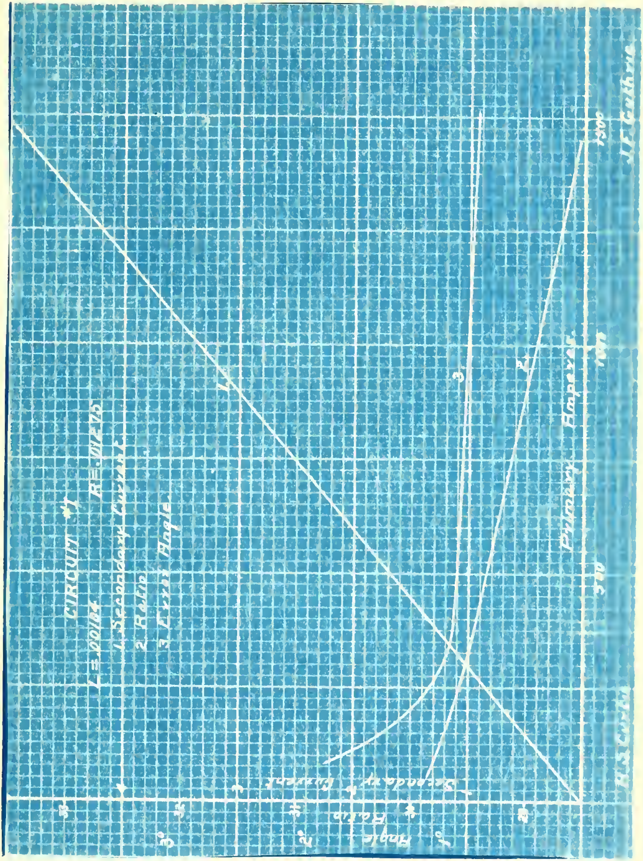
CIRCUIT #1
L=.00184 R=.01275
1 Secondary Current
2 Ratio
3 Error Angle
1
2
3
Primary Ampere
500
1000
1500
Secondary Current
Ratio
Angle

PLATE III

ARMOUR
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[illegible]

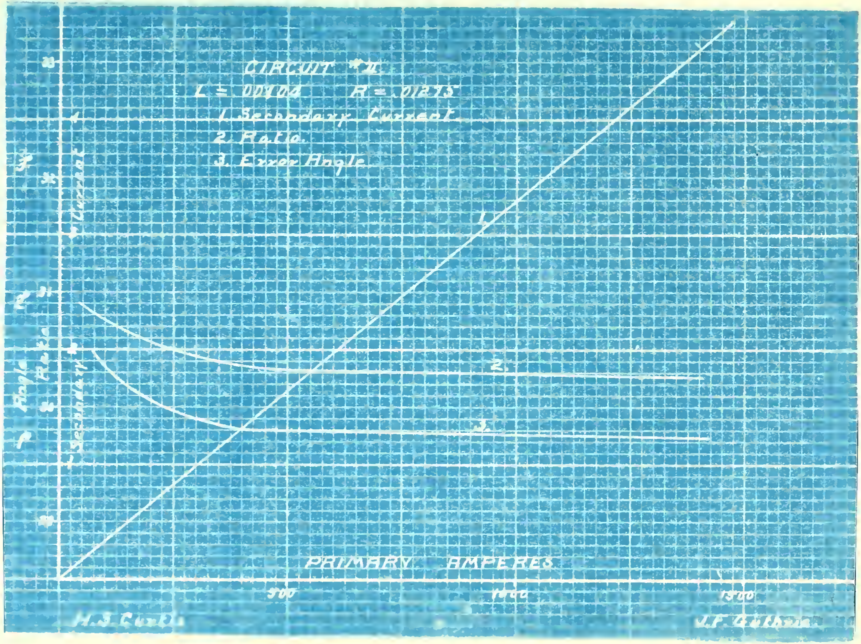
CIRCUIT #II
L = .00704 R = .01275
1. Secondary Current
2. Ratio.
3. Error Angle
1
2
3
Secondary Current
Ratio
Angle
PRIMARY AMPERES
500
1000
1500
H. S. Curtis
J. F. Guthrie

PLATE IV

ARMOUR
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LIBRARY

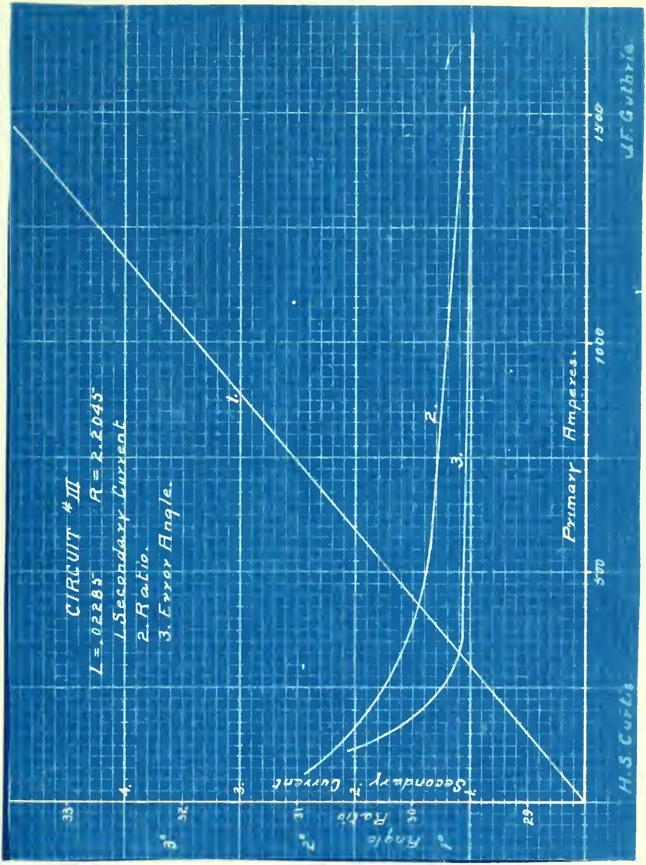
CIRCUIT # III
L = .02285
R = 2.2045
1. Secondary Current
2. Ratio.
3. Error Angle.
1.
2.
3.
Primary Amperes.
500
1000
1500
1. Secondary
2. Current
3. Ratio
4. Angle
1.
2.
3.
4.
29
30
31
32
33
1°
2°
3°
H.S. Curtis
J.F. Guthrie

PLATE V

ARMOUR
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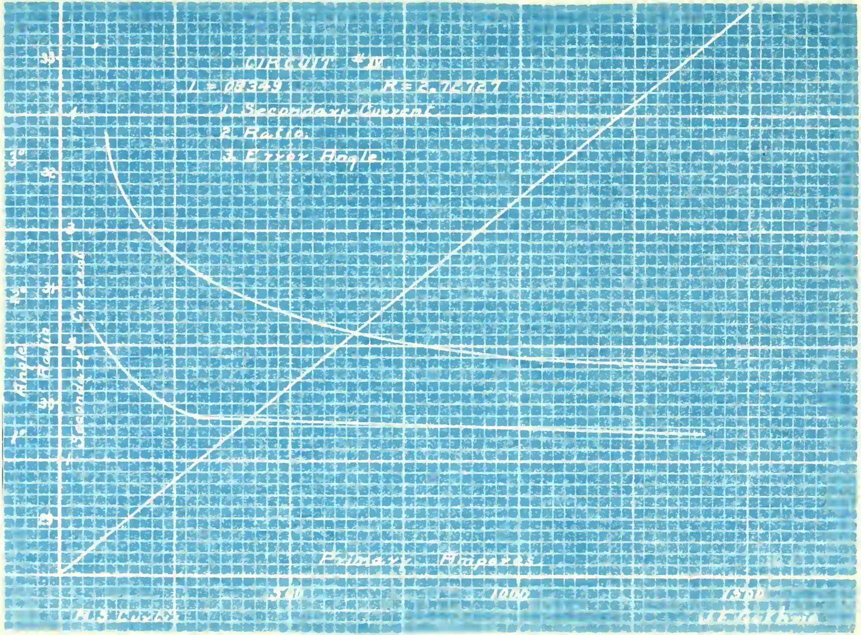
CIRCUIT #IV
L = .08349
R = 2.71727
1 Secondary Current
2 Ratio
3 Error Angle
Primary Amperes
500
1000
1500
Angle
Ratio
Secondary Current

PLATE VI

ARMOUR
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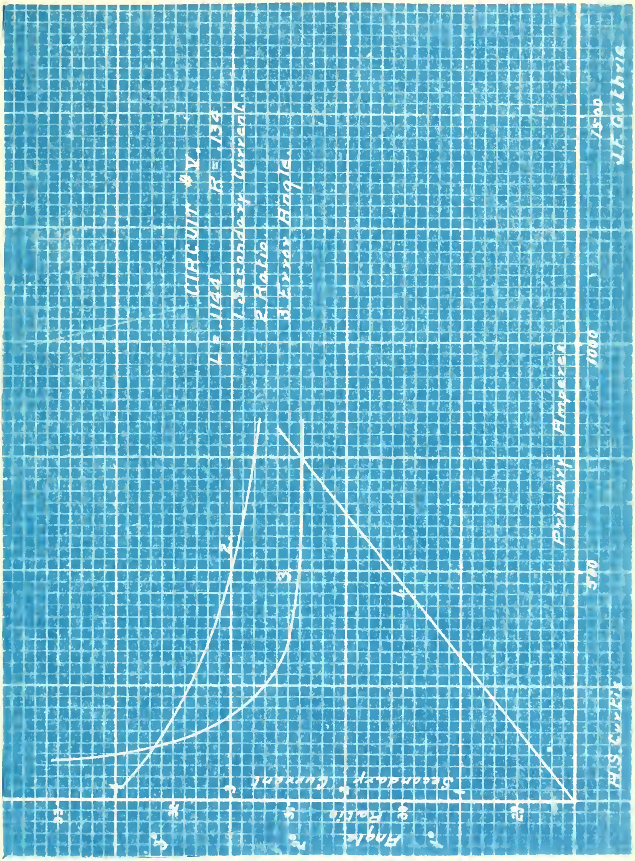
CIRCUIT #V
L = 1144 R = .134
1 Secondary Current
2 Ratio
3 Error Angle
1
2
3
Primary Amperes
500
1000
1500
Secondary Current
Ratio
Angle
J.F. Guthrie
H.S. Curtis

PLATE VII

ARMOUR
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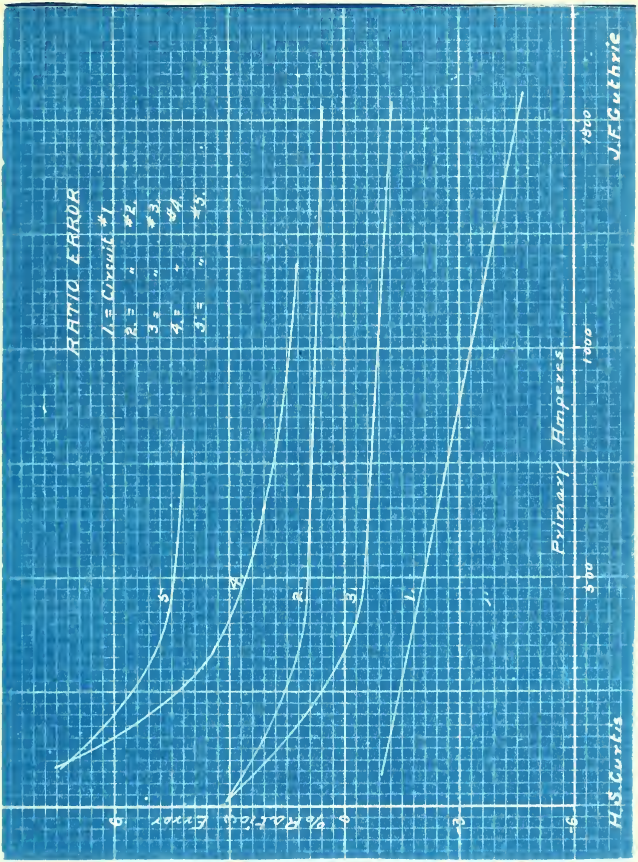
[illegible]


RATIO ERROR
1 = Circuit #1
2 = " #2
3 = " #3
4 = " #4
5 = " #5
5
4
2
3
1
1'
Primary Amperes
500
1000
1500
% Ratio Error
6
3
0
-3
-6
H.S.Curtis
J.F.Guthrie

PLAEE VIII

ARMOUR
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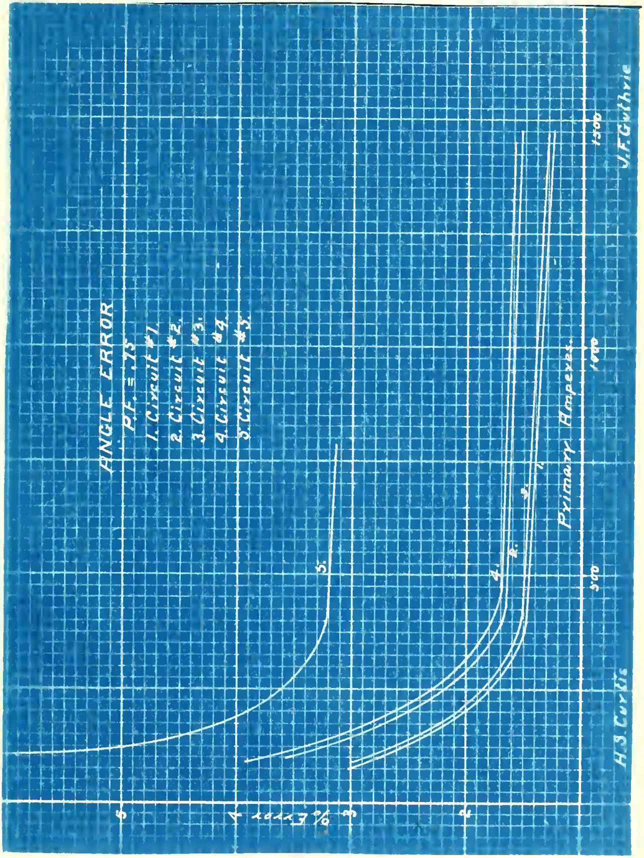
ANGLE ERROR
P.F. = .75
1. Circuit #1.
2. Circuit #2.
3. Circuit #3.
4. Circuit #4.
5. Circuit #5.
5.
4.
3.
2.
1.
Primary Amperes.
500
1000
1500
% Error
5
4
3
2
H.S.Curtis
J.F.Guthrie

PLATE IX

ARMOUR
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[illegible]

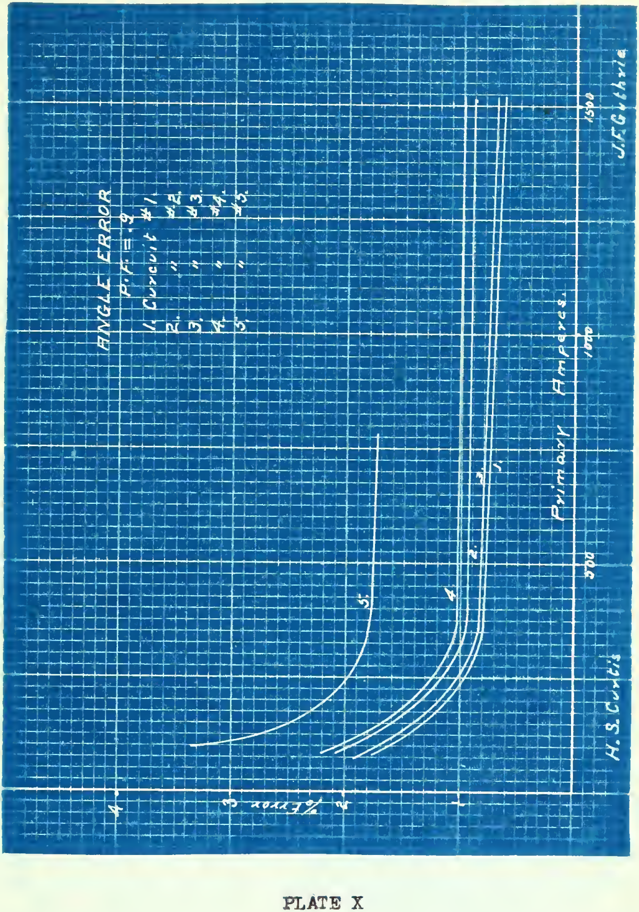
ANGLE ERROR
P.F. = .9
1. Circuit #1
2. " #2.
3. " #3.
4. " #4.
5. " #5.
Primary Amperes.
500
1000
1500
% Error
1
2
3
4
1.
2.
3.
4
5.
H. S. Curtis
J. F. Guthrie

PLATE X

ARMOUR
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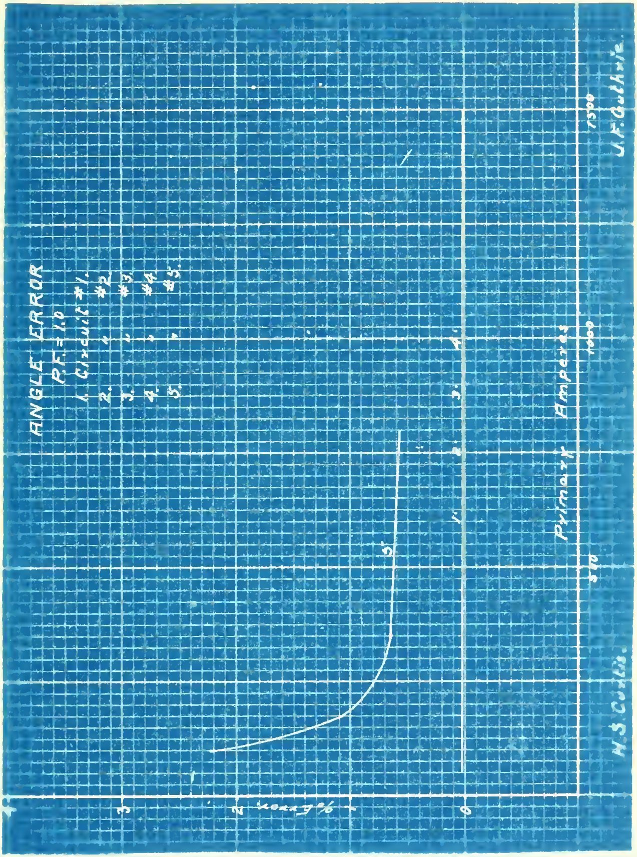
ANGLE ERROR
P.F. = 1.0
1. Circuit #1.
2. " #2
3. " #3.
4. " #4
5. " #5.
Primary Amperes
500
1000
1500
% Error
0
1
2
3
1.
2.
3.
4.
5.
H.S. Collis.
J.F. Guthrie.

PLATE XI

ARMOUR
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[illegible]

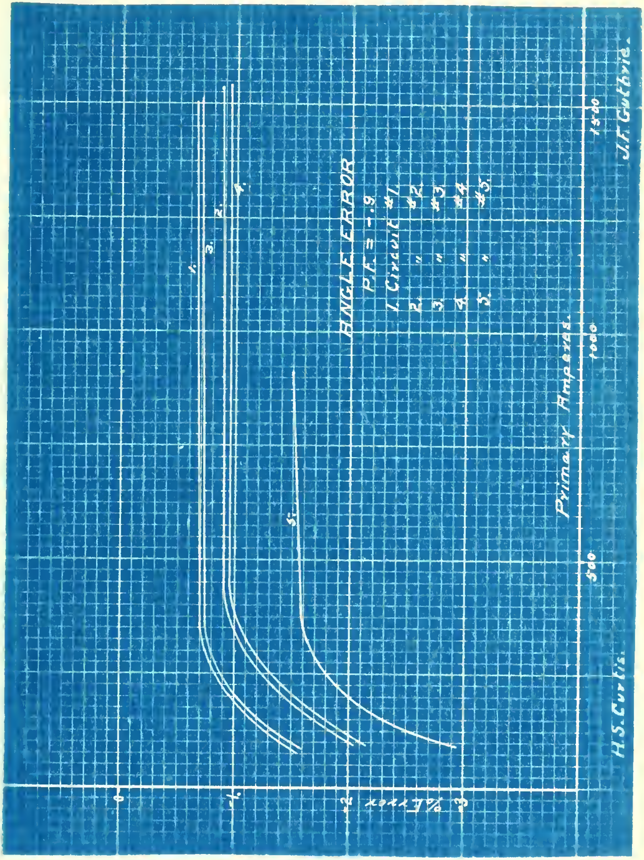
ANGLE ERROR
P.F. = -.9
1. Circuit #1
2. " #2
3. " #3
4. " #4
5. " #5
1.
3.
2.
4.
5.
Primary Amperes.
500
1000
1500
% Error
0
.1
.2
.3
H.S. Curtis.
J.F. Guthrie.

PLATE XII

ARMOUR
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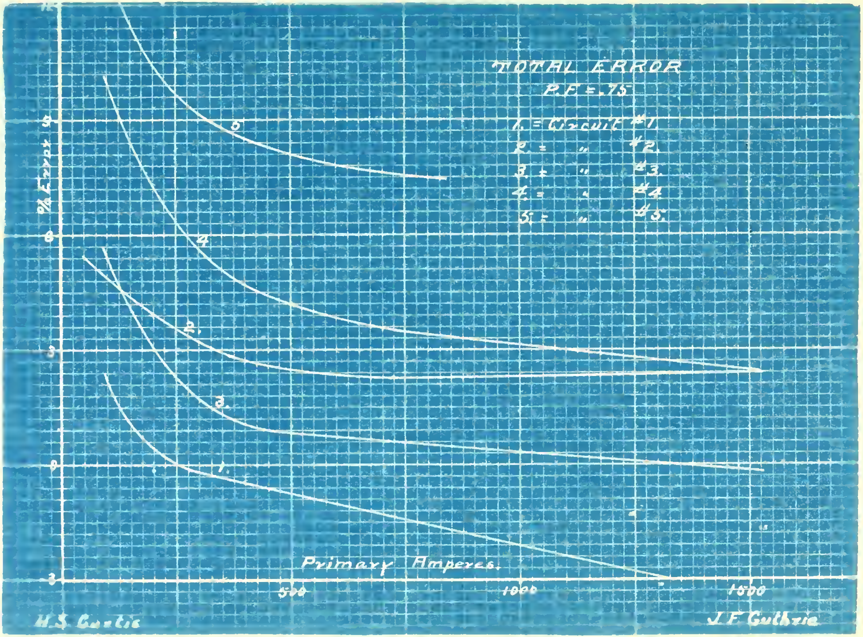
TOTAL ERROR
P.F. = .75
1. = Circuit #1
2 = " #2
3. = " #3
4. = " #4
5. = " #5
% Error
Primary Amperes.
500
1000
1500
5
4
2.
3.
1.
H.S. Curtis
J.F. Guthrie

PLATE XIII

ARMOUR
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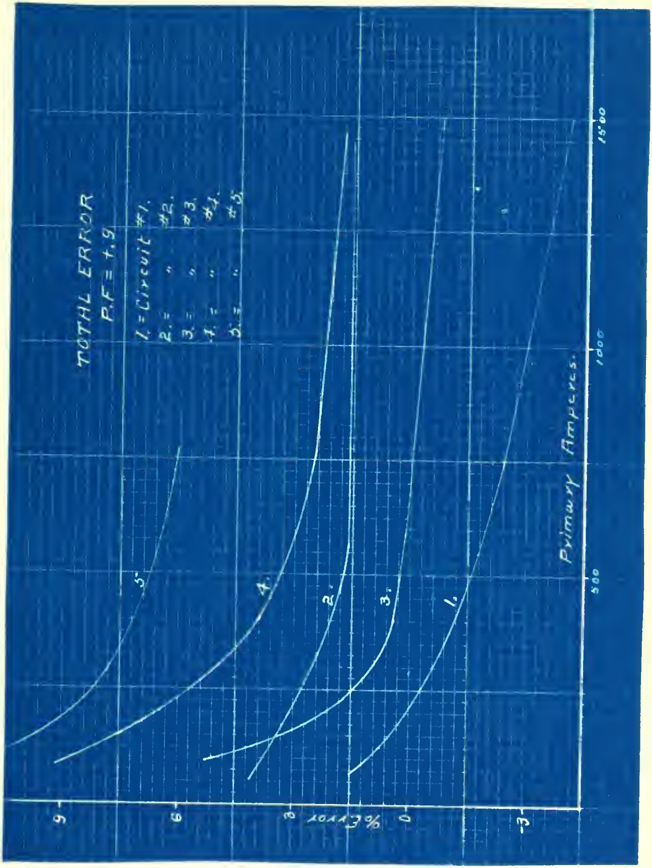
TOTAL ERROR
P.F. = +.9
1. = Circuit #1.
2. = " #2.
3. = " #3.
4. = " #4.
5. = " #5.
5.
4.
2.
3.
1.
9
6
3
0
-3
% Error
500
1000
1500
Primary Amperes.

PLATE XIV

ARMOUR
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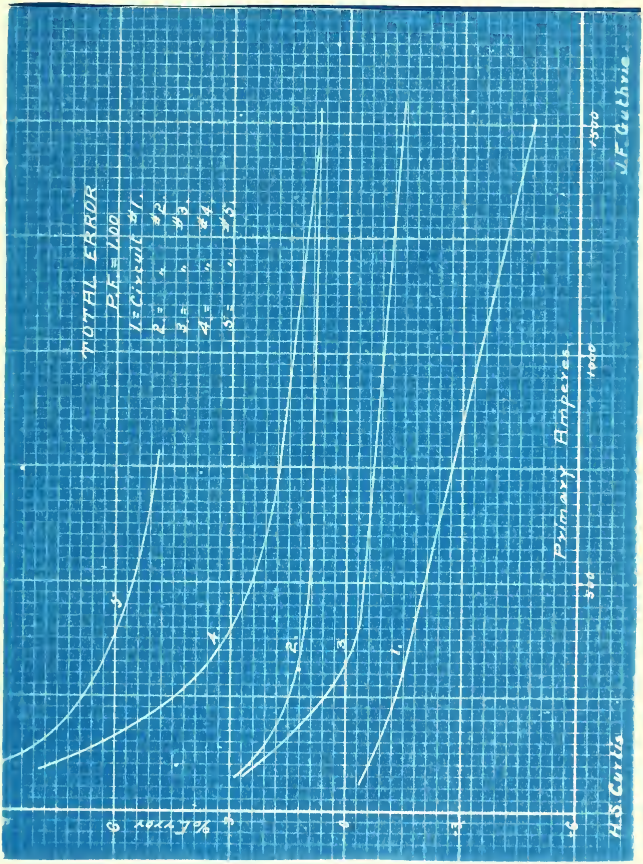
TOTAL ERROR
P.F. = 1.00
1 = Circuit #1.
2 = " " #2.
3 = " " #3.
4 = " " #4.
5 = " " #5.
Primary Amperes
500
1000
1500
%Error
.6
.3
0
.3
.6
1.
2.
3
4.
5
H.S. Curtis
J.F. Guthrie

PLATE XV

ARMOUR
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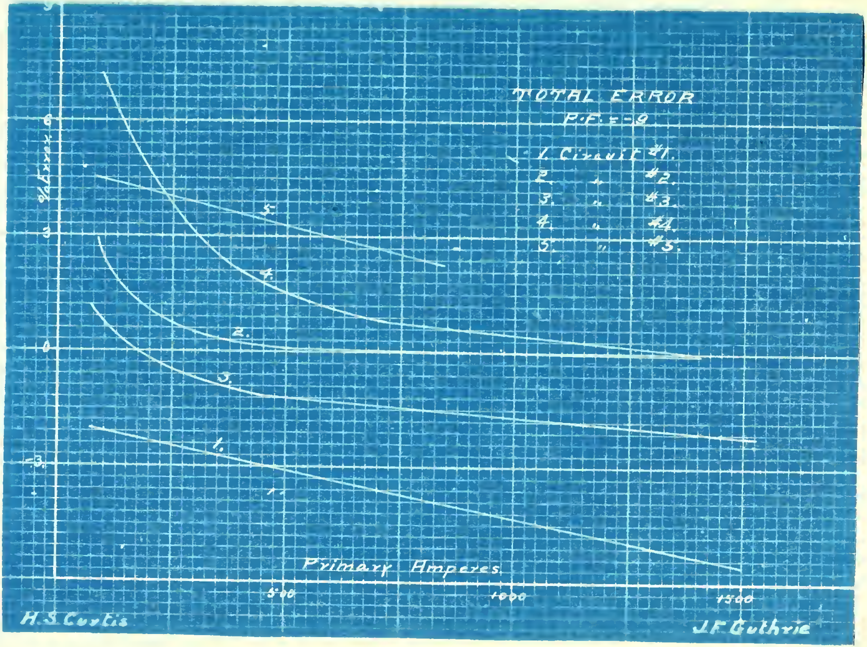
TOTAL ERROR
P.F. = .9
1. Circuit #1.
2. " #2.
3. " #3.
4. " #4.
5. " #5.
% Error
6
3
0
-3
5.
4.
2.
3.
1.
Primary Amperes.
500
1000
1500
H.S. Curtis
J.F. Guthrie

PLATE XVI

ARMOUR
INSTITUTE OF TECHNOLOGY
LIBRARY

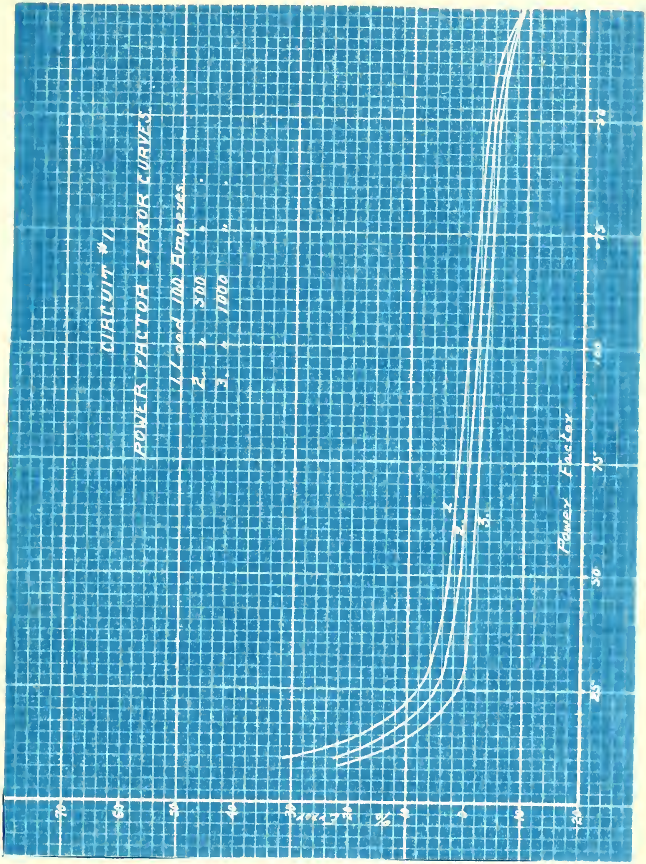
CIRCUIT #1
POWER FACTOR ERROR CURVES
1. Load 100 Amperes
2. " 500 "
3. " 1000 "
1.
2.
3.
Power Factor
50
75
100
75
50
25
70
60
50
40
30
Error
20
%
10
0
10
20

PLATE XVII

ARMOUR
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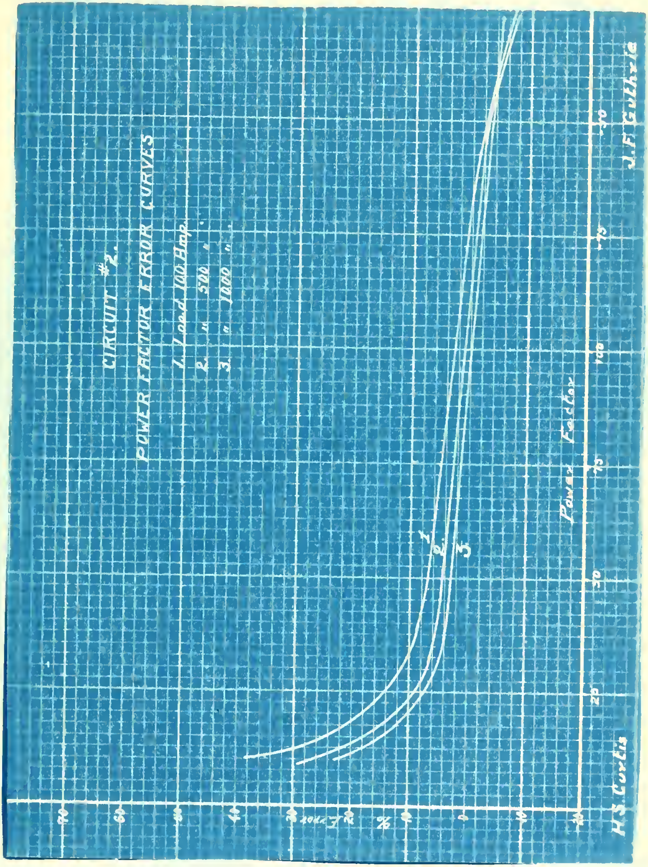
CIRCUIT #2.
POWER FACTOR ERROR CURVES
1. Load 100 Amp.
2. " 500 "
3. " 1000 "
1
2
3
Power Factor
25
50
75
100
75
50
% Error
70
60
50
40
30
20
10
0
10
20
H.S. Curtis
J.F. Guthrie

PLATE XVIII

ARMOUR
INSTITUTE OF TECHNOLOGY
[illegible]

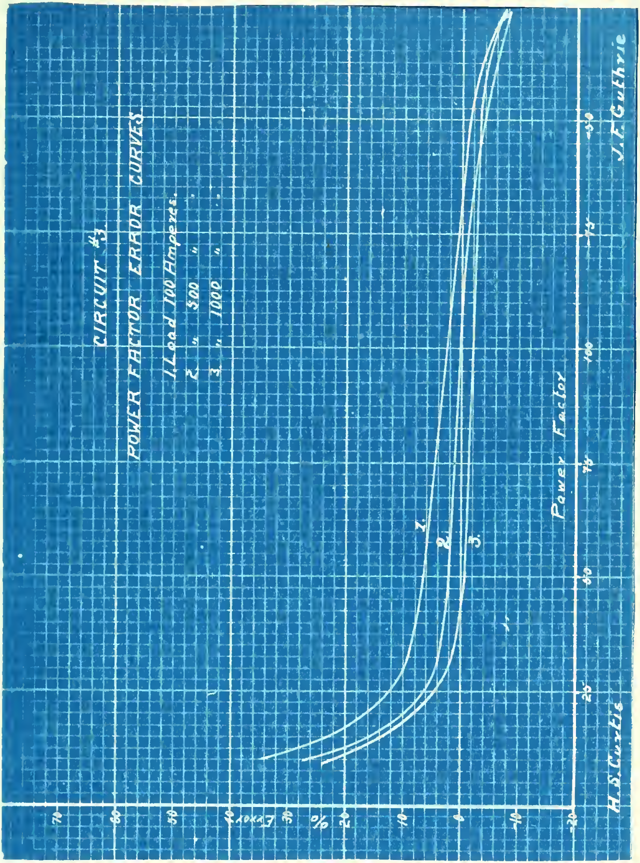
CIRCUIT #3.
POWER FACTOR ERROR CURVES
1. Load 100 Amperes.
2 " 500 "
3 " 1000 "
1.
2.
3.
Power Factor
Error
%
70
60
50
40
30
20
10
0
-10
-20
25
50
75
100
75
50
H. S. Curtis
J. F. Guthrie

PLATE XIX

ARMOUR
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LIBRARY

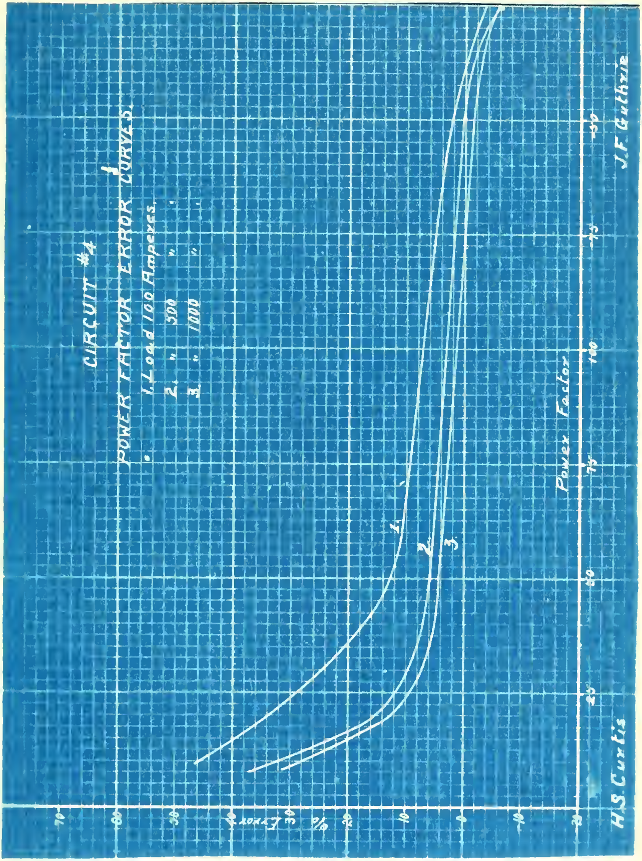
CIRCUIT #4
POWER FACTOR ERROR CURVES.
1. Load 100 Amperes.
2. " 500 "
3. " 1000 "
1.
2.
3.
Power Factor
% of Error
70
60
50
40
20
10
0
-10
-20
25
50
75
100
75
50
H.S. Curtis
J.F. Guthrie

PLATE XX

ARMOUR
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LIBRARY

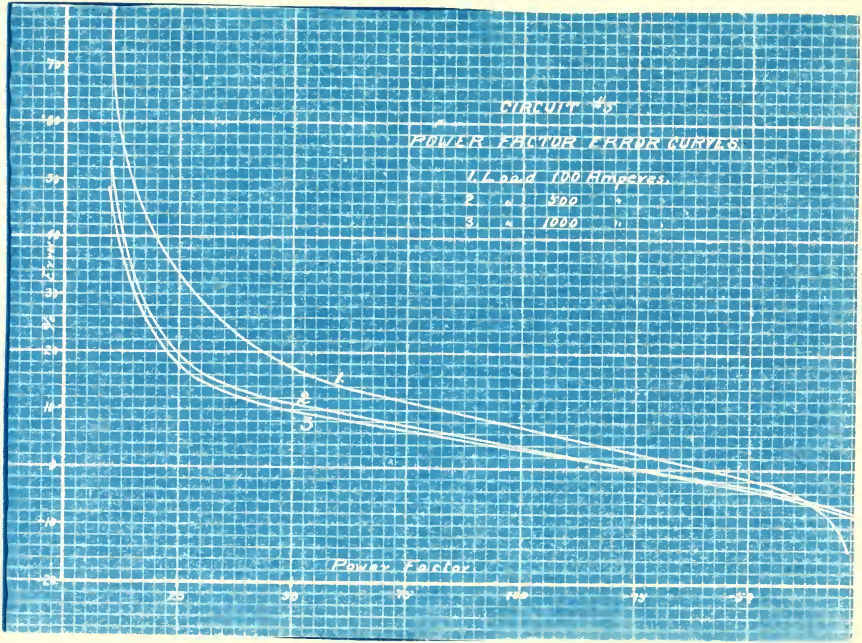
CIRCUIT #5
POWER FACTOR ERROR CURVES.
1. Load 100 Amperes.
2 " 500 "
3 " 1000 "
1.
2
3
Power Factor
25
50
75
100
75
50
70
60
50
40
% Errors
30
20
10
0
-10
-20

PLATE XXI

ARMOUR
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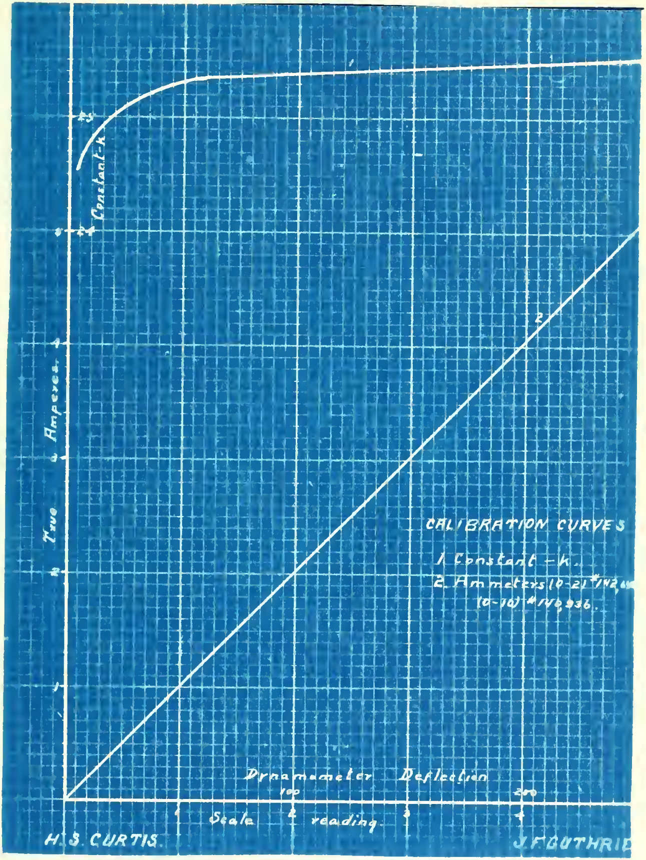
LIBRARY



.25
.24
5
4
3
2
1
Constant-k
1
2
True Amperes.
CALIBRATION CURVES
1. Constant-k.
2. Ammeters (0-2) #142,
(0-10) #140,936.
Dynamometer Deflection
100
200
1
Scale
2
reading.
3
4
H. S. CURTIS.
J. F. GUTHRIE

PLATE XXII

ARMOUR
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LIBRARY

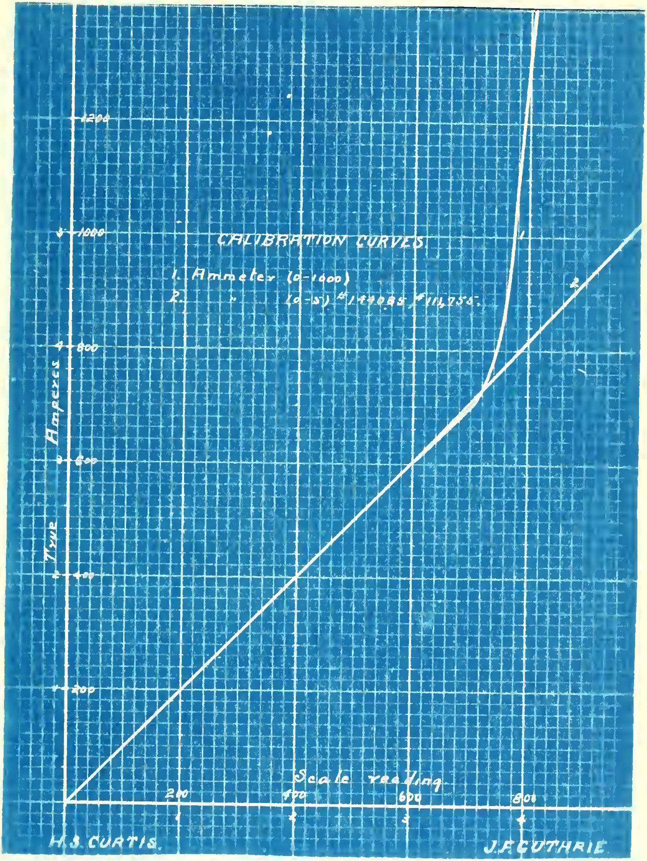
CALIBRATION CURVES.
1. Ammeter (0-1600)
2. " (0-5) #144085 #11,755.
1
2
True Amperes
1200
5 1000
4 800
3 600
2 400
1 200
Scale reading
200
400
600
800
1
2
3
4
H.S. CURTIS.
J.F. GUTHRIE.

PLATE XXIII

ARMOUR
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LIBRARY

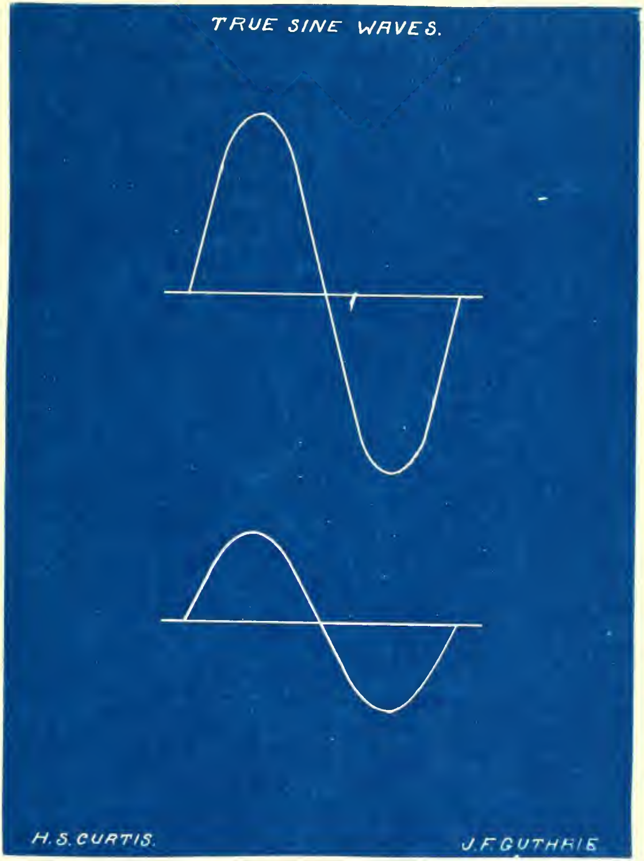

PLATE XXIV

ARMOUR
INSTITUTE OF TECHNOLOGY
LIBRARY

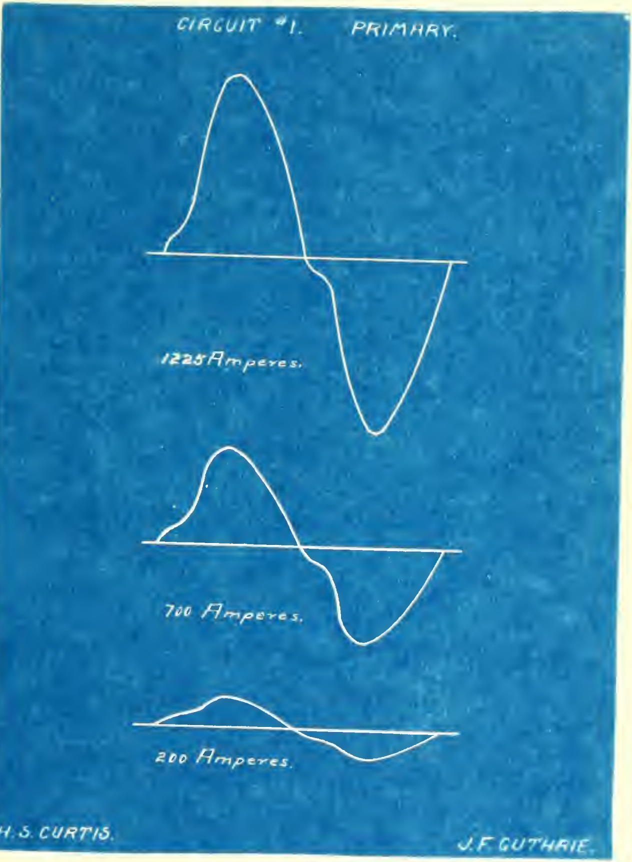
CIRCUIT #1. PRIMARY.
1225 Amperes.
700 Amperes.
200 Amperes.
H. S. CURTIS.
J. F. GUTHRIE.

PLATE XXV

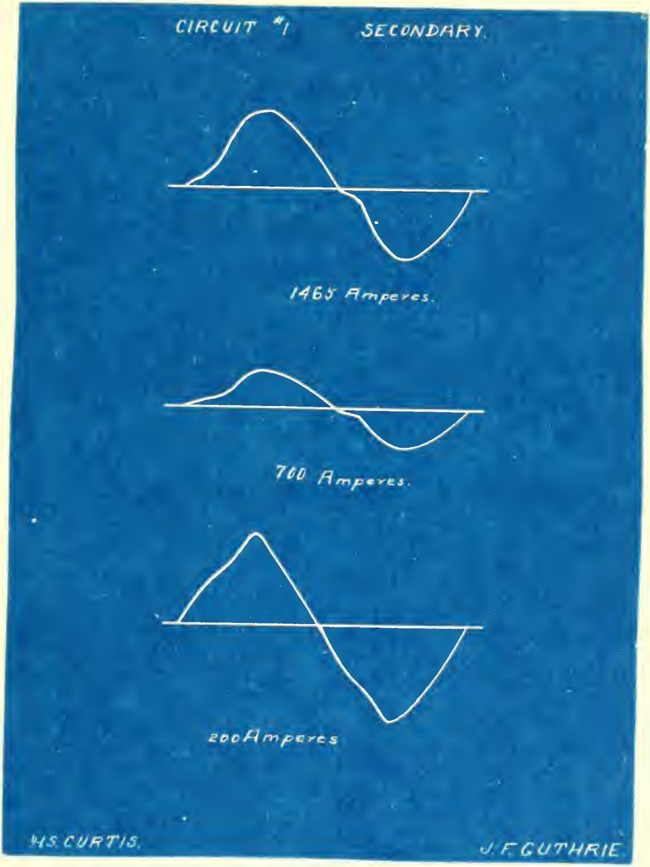
CIRCUIT #1 SECONDARY.
1465 Amperes.
700 Amperes.
200 Amperes
H.S. CURTIS.
J. F. GUTHRIE

PLATE XXVI

ARMOUR
INSTITUTE OF TECHNOLOGY
LIBRARY

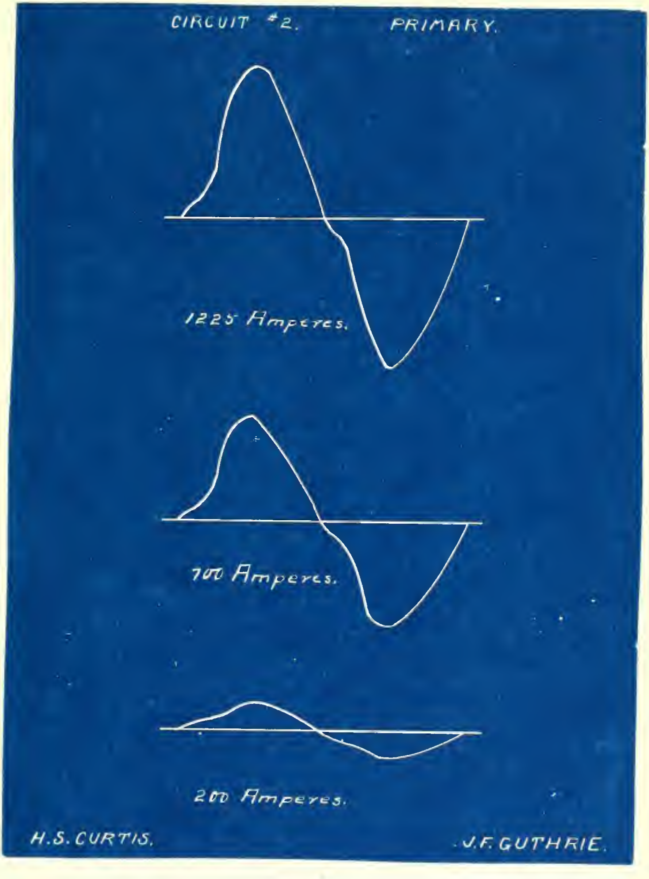
CIRCUIT #2.
PRIMARY.
1225 Amperes.
700 Amperes.
200 Amperes.
H.S. CURTIS.
J.F. GUTHRIE.

PLATE XXVII

ARMOUR
INSTITUTE OF TECHNOLOGY
LIBRARY

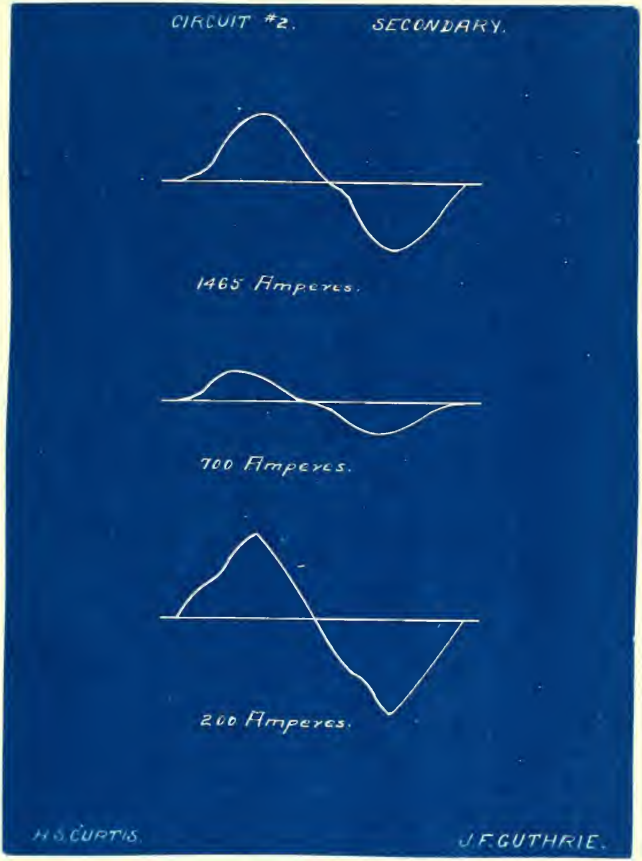

PLATE XXVIII

ARMOUR
INSTITUTE OF TECHNOLOGY
LIBRARY

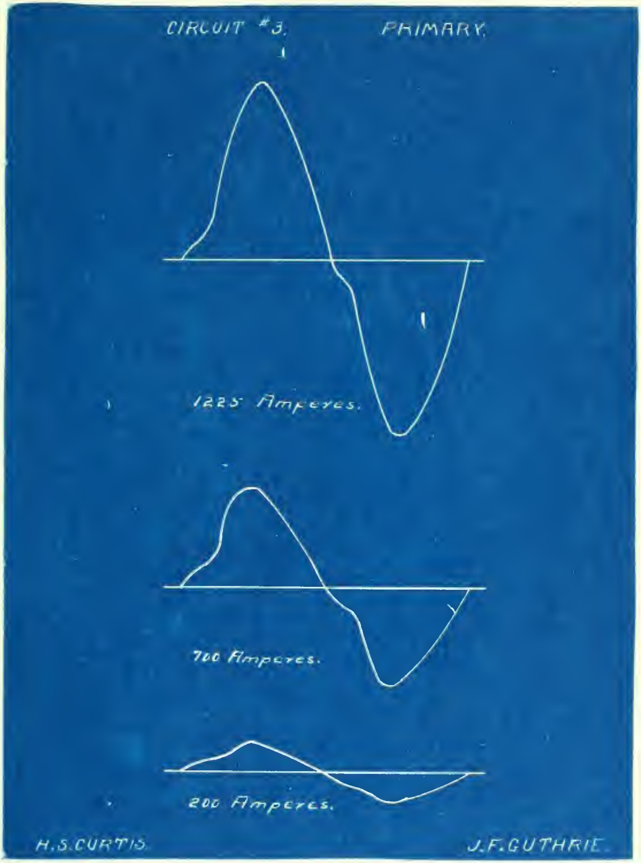
CIRCUIT #3.
PRIMARY.
1225 Amperes.
700 Amperes.
200 Amperes.
H.S. CURTIS.
J.F. GUTHRIE.

PLATE XXVIX

ARMOUR
INSTITUTE OF TECHNOLOGY
LIBRARY

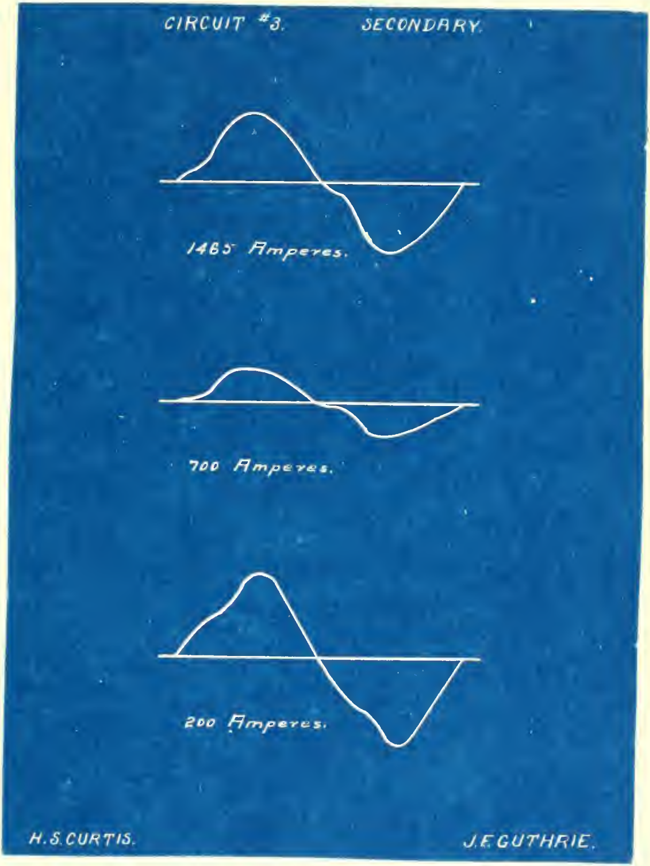
CIRCUIT #3. SECONDARY.
1465 Amperes.
700 Amperes.
200 Amperes.
H.S.CURTIS.
J.F.GUTHRIE.

PLATE XXX

ARMOUR
INSTITUTE OF TECHNOLOGY
LIBRARY

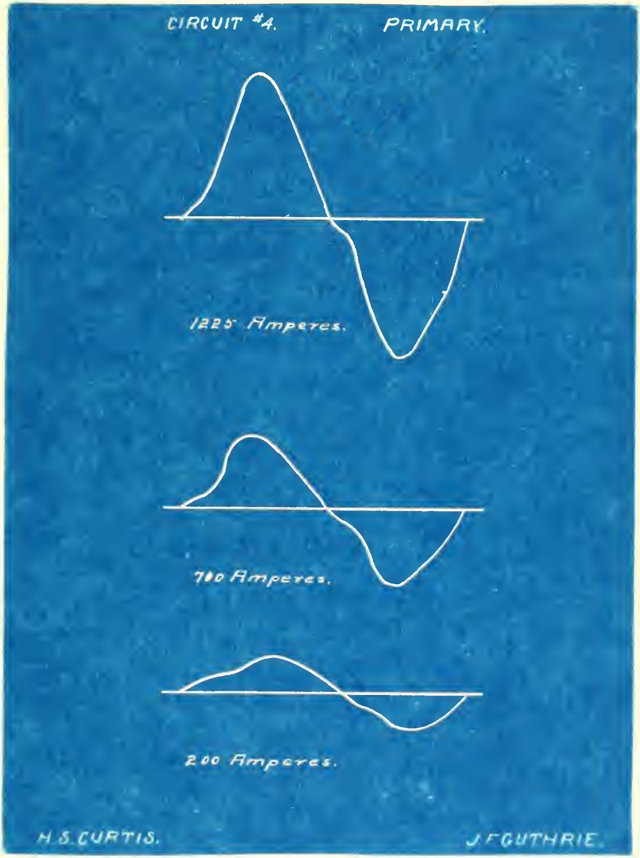
CIRCUIT #4.
PRIMARY.
1225 Amperes.
700 Amperes.
200 Amperes.
H.S.CURTIS.
J.F.GUTHRIE.

PLATE XXXI

ARMOUR
INSTITUTE OF TECHNOLOGY
LIBRARY

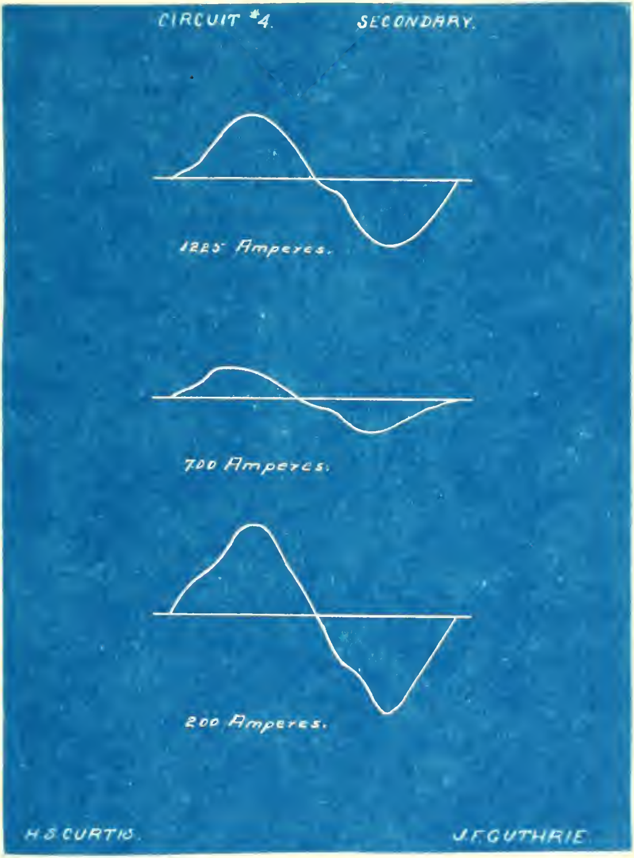
CIRCUIT #4.
SECONDARY.
1225 Amperes.
700 Amperes.
200 Amperes.
H.S. CURTIS.
J.F. GUTHRIE.

PLATE XXXII

ARMOUR
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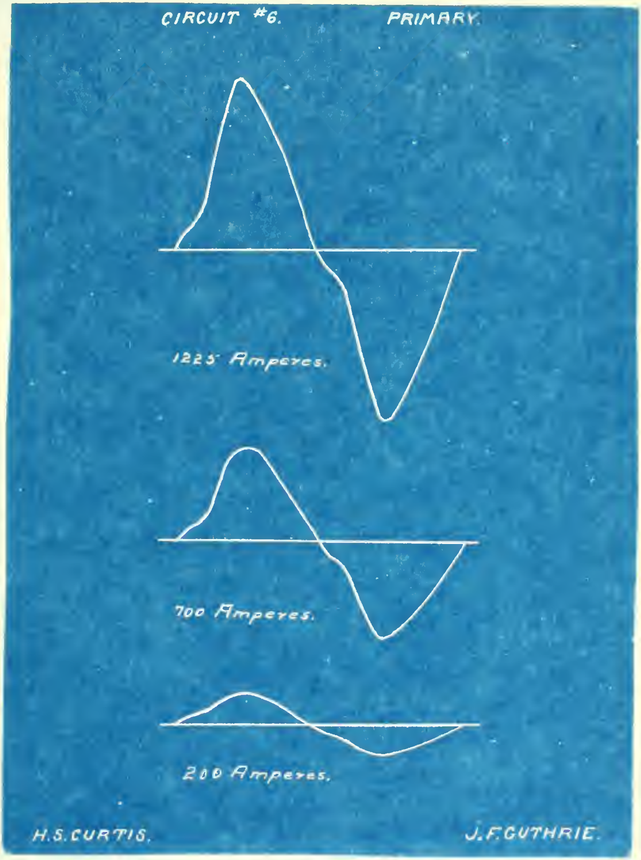

PLATE XXXIII

ARMOUR
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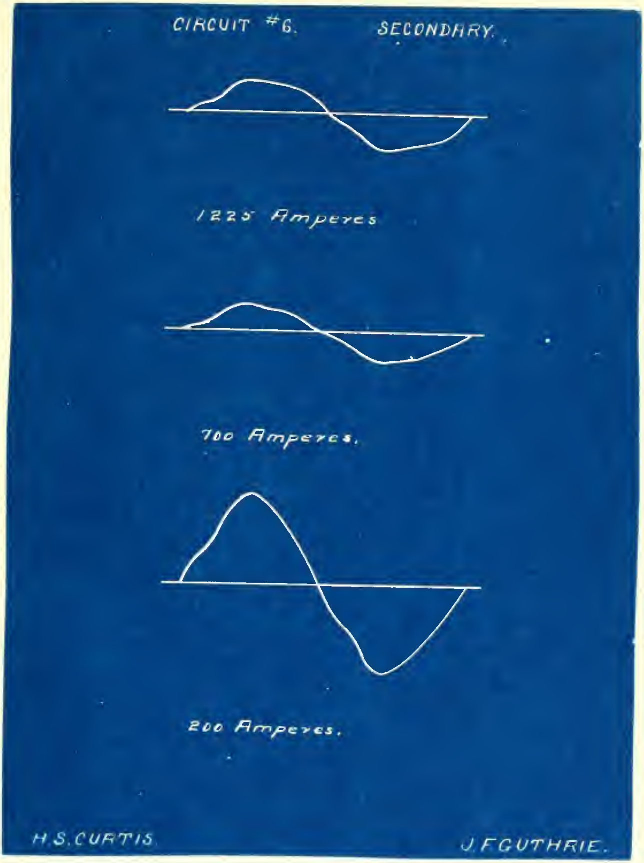
CIRCUIT #6.
SECONDARY.
1225 Amperes
700 Amperes.
200 Amperes.
H.S. CURTIS.
J.F GUTHRIE.

PLATE XXXIV

ARMOUR
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